Revue Scientifique. Juillet—Décembre, 1890. 4to. *Paris.* The Editor.

Symons's Monthly Meteorological Magazine. July to December, 1890. 8vo. *London.* Mr. G. J. Symons, F.R S.

Zeitschrift für Biologie. Bd. XXVII. Heft 2–3. 8vo. *München* 1890. The Editors.

Mezzotint Engraving of Sir W. Bowman, Bart., F.R.S., from the painting by W. W. Ouless, R.A., exhibited at the Royal Academy, 1889. The Committee of Subscribers.

January 15, 1891.

Sir WILLIAM THOMSON, D.C.L., LL.D., President, in the Chair.

The Presents received were laid on the table, and thanks ordered for them.

The following Papers were read :—

I. "On the Rate of Propagation of the Luminous Discharge of Electricity through a Rarefied Gas." By J. J. THOMSON, M.A., F.R.S., Cavendish Professor of Experimental Physics, Cambridge. Received January 2, 1891.

Though the determination of the velocity of propagation of the luminosity which accompanies the electric discharge through gases might well be expected to throw considerable light on the means by which the discharge is effected, as far as I can find, no attempts seem to have been made in this direction since Wheatstone, in 1835, observed the appearance presented in a rotating mirror of the discharge through a vacuum tube 6 feet long; he concluded from his observations that the velocity with which the flash went through the tube could not have been less than 2×10^7 cm. per second. This very great velocity does not seem to be accompanied by a correspondingly large velocity of the luminous molecules, for von Jahn (Wiedemann's 'Annalen,' vol. 8, 1879, p. 675) has shown that the lines of the spectrum of the gas in the discharge tube are not displaced by as much as 1/40 of the distance between the D lines when

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the line of sight is in the direction of the discharge tube. It follows from this, by Döppler's principle, that the particles when emitting light are not travelling in the direction of the discharge at the rate of more than a mile a second, proving at any rate that the luminosity does not consist of a wind of luminous particles travelling with the velocity of the discharge.

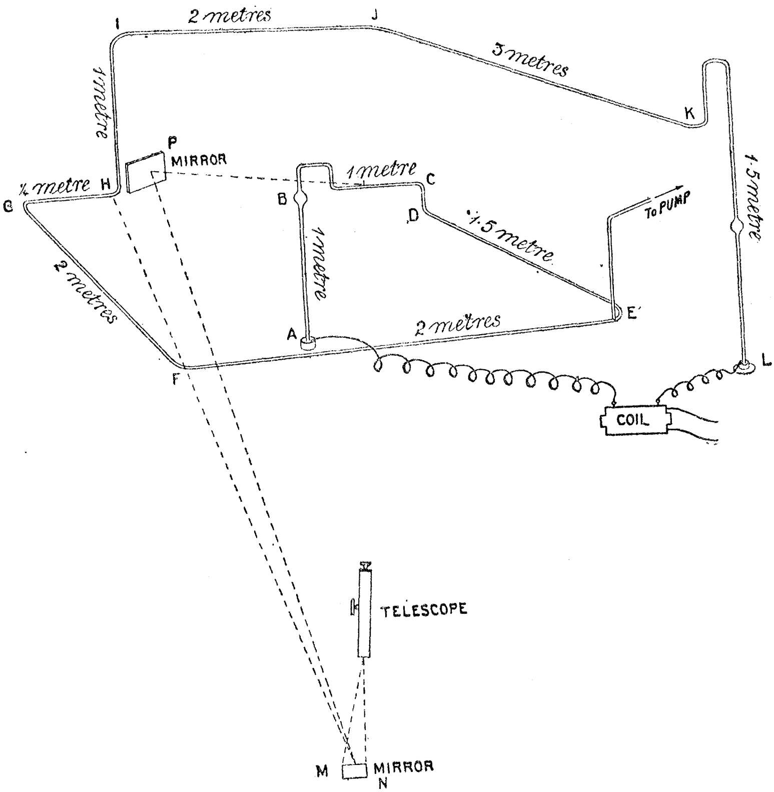
Wheatstone's observations only give an inferior limit to the velocity of the discharge. Nothing was observed in these which indicated that the velocity of discharge was finite. A method which would enable us to measure this velocity would also at the same time show whether the discharge always started from the positive or negative end of the tube, and so enable us to trace the course of the discharge.

In the following experiments I have endeavoured to measure this velocity, and also to ascertain whether the main discharge starts from the anode or the cathode. The long tubes used in my experiments were practically filled by the positive column; thus in the tube 50 feet long the positive column extends to within an inch or two of the cathode. All the experiments described below relate to the behaviour of the positive column.

Plücker (Poggendorff's 'Annalen,' vol. 107, 1859, p. 89) concludes from the action of a magnet on the discharge that it starts from the anode. This conclusion does not seem to have met with much acceptance; my experiments, however, fully bear it out, as I find that, except under exceptional circumstances, which will be described later, the luminosity of the positive column begins close to the anode and travels away from it.

The experiments for measuring the velocity of the luminous column were after several preliminary trials finally arranged in the following way. ABCDEFG.... L (fig. 1) is a glass tube about 15 metres long and 5 mm. in diameter, which, with the exception of two horizontal pieces of BC and GH, is covered with lamp black; this tube is exhausted, and a current sent through it from a coil giving sparks 6 or 7 inches long in air; the light from the uncovered portions falls on a rotating mirror MN, placed at a distance of about 6 metres from BC; the light from GH falls on the rotating mirror directly, that from BC after reflection from the plain mirror P. The images of the bright portions of the tube after reflection from the revolving mirror are viewed through a telescope, and the mirrors are so arranged that when the revolving mirror is stationary the images of the bright portions of the tube appear as portions of the same horizontal straight line. The terminals of the long vacuum tube are pushed through mercury up the vertical tubes AB, KL. This arrangement was adopted because by running sulphuric acid up these tubes the terminals could readily be changed from pointed platinum wires to flat liquid sur-

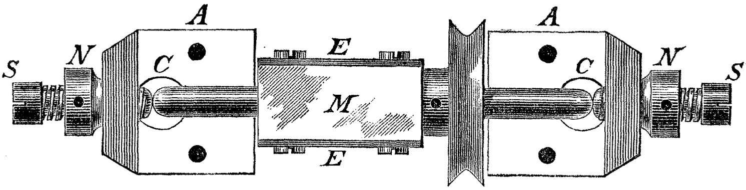
Fig. 1.



faces, and the effect of very different terminals on the velocity and direction of the discharge readily investigated. The bulbs in these vertical tubes were also found very useful as receptacles for sulphuric acid for drying the gas left in the tube.

The revolving mirror was driven at a speed varying from 400 to 500 per second by a Gramme machine through which the current from twelve large storage cells was sent. The mirror first used was mounted on ball bearings such as are used for bicycles; the axle had, however, too much play, and it was eventually discarded for one made by the Cambridge Scientific Instrument Company, and designed by Mr. Bartlett, the assistant at the Cavendish Laboratory. It is represented full size in fig. 2. The spindle carrying the mirror M runs on parallel bearings in the uprights A, A. The ends of the spindle are rounded, hardened, and polished, and are in line with but just do not

FIG. 2.



Plan of Revolving Mirror. Upper halves of Bearings, A, carrying Oil Cup removed.

touch two set screws, S, S, whose ends are also rounded, hardened, and polished. Directly beneath the end of each axle is a cavity, C, which serves to hold the oil running down from oil cups placed immediately above. This arrangement was found to lubricate so well that there was no appreciable heating even after long runs. The spindle is made from square steel, the ends being turned down, and against two opposite sides of the square centre portion, clutches E, E, for holding the mirror M, are fastened. The whole is accurately balanced. The bearings are attached to a heavy iron casting, which is firmly bolted down to a heavy piece of masonry.

In order to get a sufficiently rapid rotation of the revolving mirror the Gramme had to be geared up. This was done by means of pulleys mounted on ball bearings.

A great many arrangements were tried in order to break the primary circuit of the coil, when the mirror was in such a position that the images of the luminous part of the tube would be reflected by it into the telescope; after a great deal of time had been spent over these they were all given up. The reason why they will not work is pretty clear. The coil will not work when the primary circuit is broken anything like so often as 500 times a second, so that if the primary is to be broken by the mirror there must be very considerable gearing down between the mirror and the break, in other words, the mirror can be moved through a very considerable angle without moving the break through more than a very small distance, but almost the smallest possible movement of the mirror is sufficient to send the images out of the field of view; and it was found impossible to diminish the play between the mirror and the break to such an extent as to ensure that at a high rate of rotation the break took place synchronously with the requisite position of the mirror. The method finally adopted was the primitive one of using an independent mercury break driven by a small Thirlmere water motor, and patiently looking through the telescope until the break happened to occur just at the right moment. This, though a somewhat lengthy proceeding, was not found in practice to be any longer than when synchronism be-

tween the break of the coil and the position of the mirror was attempted by artificial means.

When the observations were made in this way, the observer at the telescope saw, on an average about once in four minutes, sharp bright images of the portions BC and GH of the tube, not sensibly broadened, but no longer quite in the same straight line; the relative displacement of these lines was reversed on reversing the coil, and also on reversing the direction of rotation of the mirror. These bright images are not the only ones observed through the telescope; ill-defined and widened images were much more frequent; sometimes these were widened out so as to fill the whole field of view with a luminous haze, at others, the images appeared as broad bands, the boundaries of these bands not being in the same straight line; these images indicate a discharge lasting for a very much longer time than that which produced the bright sharp images which were the object of our attention. When these sharp images were very bright, it could be distinctly seen that they were striated.

The displacement of the images from the same straight line is due to the finite velocity with which the luminosity is propagated; for if the mirror can turn through an appreciable angle while the luminosity travels from BC to GH, or *vice versâ*, these images of BC and GH, as seen in the telescope after reflection from the revolving mirror, will no longer be in the same straight line, but if the mirror is turning so that, on looking through the telescope, the images seem to come in at the top and go out at the botton of the field of view, the image of that part of the tube at which the luminosity appears first will be raised above that of the other. If we know the rate of rotation of the mirror, the vertical displacement of the images and the distance between BC and GH, the rate of propagation of the luminosity may be calculated. The observations were made in the following way:—The tube having previously been properly dried and exhausted, so that the discharge would pass freely through it, one observer took his seat at the telescope, the room was then darkened, and the coil set in action by another observer, the observer at the telescope not knowing which of the electrodes was positive and which negative; the mirror was then set in rotation, and about once in four minutes, on an average, the observer at the telescope saw the bright sharp images alluded to above. When the observer had seen two or three of these, he stated whether they were very bright, fairly bright, or indistinct; which image was the higher, and by how much. The distance between the images was estimated in terms of the apparent distance between the divisions of a vertical millimetre scale placed at GH when seen through the telescope; the scale was not seen at the same time as the image of the tube, so that the observation cannot claim any great accuracy; different observers agree, however, under the same circum-

stances to within 25 per cent, and it is probable that, in our present state of knowledge about the discharge of electricity through gases, the points of most importance can be settled by a somewhat rough determination of the velocity of propagation.

Some hundreds of observations were made, and in every case in which the observer declared the images to be very bright, and in every case but one in which the images were declared to be fairly bright, the displacements (if there was not a *very* large air break in the circuit) corresponded to the luminosity travelling from the positive to the negative electrode. When AB was the negative electrode, the luminous discharge arrived at GH, a place about 25 feet from the positive electrode, before it reached BC, which is only a few inches from the cathode, and as the interval between its appearance at these places was about the same as when the current was reversed, we may conclude that, when AB is the cathode, the luminosity, which is found only a few inches from it at BC, has started from the positive electrode, and traversed a path enormously longer than its distance from the cathode.. We thus arrive at the conclusion that the positive column, which in a long tube like the one under consideration practically fills the tube, since it extends to within an inch or two of the anode, starts from the positive electrode.

In view of the probability that the passage of the current from the electrodes to the gas might be largely influenced by chemical action between the electrode and the gas, I repeated the experiments with electrodes of very different kinds; the result, however, was the same, whether the electrodes were pointed platinum wires, carbon filaments, flat surfaces of sulphuric acid, or the one electrode a flat liquid surface and the other a sharp pointed wire. The positive column starts from the positive electrode, even though this is a flat liquid surface while the negative is a sharp-pointed wire.

Velocity of Propagation of the Discharge.

The displacement of the images of the two luminous portions of the tube caused by the rotation of the mirror was equal to the distance between the images of divisions 1·5 mm. apart on a vertical scale placed at GH. Thus, if T is the time the luminosity takes to travel from BC to GH, since the distance of the mirror from the luminous part of the tube is 6 metres, the circular measure of the angle turned through in the time T is 1·5/12,000. If n is the number of revolutions made by the mirror per second,

$$T = \frac{1 \cdot 5}{12{,}000 \times 2\pi n}.$$

When the mirror was running at full speed, its rate was pretty constant and, as determined by the note given out in a telephone (taken for the sake of avoiding the noise made by the Gramme and mirror to an adjoining room) when the circuit was broken once in each revolution of the mirror, and also by the velocity of the band driving the mirror, was about 480 per second. The distance between the places BC and GH is 7 metres, so that if v is the rate at which the luminosity of the positive column travels,

$$T = \frac{700}{v};$$

hence

$$v = 12000 \times 2\pi \times 480 \times 700 \times \frac{1}{1{\cdot}5}$$

$$= 1{\cdot}6 \times 10^{10},$$

or rather more than half the velocity of light; but, as I explained before, this must be regarded as an approximation, rather than as an accurate determination. It is sufficient, however, to show that the luminosity of the positive column travels through a vacuum tube with a velocity comparable to that of light.

The preceding results hold when there is a short air break in the circuit, but, if the air break is increased until the coil can only spark through the tube with difficulty, the luminosity seems inclined to start from the air-break electrode, and the direction in which it travels is not always reversed by reversing the coil.

The fact that the main portion of the luminous discharge in a long vacuum tube has its origin at the positive electrode may appear at first sight inconsistent with the result that glow discharge takes place more easily, that is, with a smaller value of the electromotive intensity, at the negative than at the positive electrode. Thus Faraday states that the discharge from a sphere takes place more easily when the sphere is negatively than when it is positively electrified.

Again, ultra-violet light can produce a discharge from a negatively but not from a positively electrified piece of metal. Thus Lenard and Wolf (Wiedemann's 'Annalen,' vol. 37, 1889, p. 443) have proved that we can produce a cathode by allowing ultra-violet light to fall on a negatively electrified plate, while no discharge occurs if the plate is positively electrified, and Hallwachs (Wiedemann's 'Annalen,' vol. 34, 1888, p. 731) and Righi have shown that when ultra-violet light falls on an unelectrified piece of metal the metal becomes positively charged, *i.e.*, the light converts it into a cathode.

These considerations do not, however, seem to affect the question we are considering when the electromotive force is sufficiently great

to produce a discharge from the positive electrode; a much more important consideration in this case is the relative time required by the two electricities to leave their respective electrodes. If the time taken by the positive electricity to leave the anode is very much less than that taken by the negative to leave the cathode, and especially if this second time is greater than the time taken by the luminosity to pass over a considerable length of the tube, there could be no difficulty in understanding how the luminosity of the positive column, which in these experiments practically fills the tube, should have its origin at the anode.

Now, Spottiswoode and Moulton, in their very remarkable paper on the "Sensitive State of the Electric Discharge" ('Phil. Trans.,' 1879, p. 165), investigated the relative magnitudes of the times occupied by the various processes which go to make up the electric discharge, and by means of the phenomena which are observed in the revocation of what are called by them relief effects, show (1) that the time taken by the negative electricity to leave the cathode is so much longer than the time taken by the positive electricity to leave the anode, that the two times may be considered to belong to different orders of small quantities; and (2) that the time taken by the negative electricity to leave the cathode is greater than the time taken by the luminosity to travel over the length of the tube (in their case the tube was not very long); remembering these facts, the result which we have obtained by the use of the revolving mirror need occasion us no surprise.

These experiments lead us to regard the discharge as the sweeping down of the positive electricity from the anode with an enormous velocity (about half that of light in our experiments), accompanied by what is comparatively a very slow discharge from the cathode.

The fact that the positive electricity leaves the anode more quickly than the negative does the cathode, explains a very prominent feature of the electric discharge: the accumulation of positive electricity in the neighbourhood of the cathode. The positive electricity arrives at the region surrounding the cathode before the discharge from this terminal is completed; thus there will, during the greater part of the discharge from the cathode, be an excess of free positive electricity in the neighbourhood of the electrode, and, if the discharges succeed each other with sufficient rapidity, the positive electricity will accumulate until the effect of its attraction is sufficiently great to cause the negative electricity to leave the cathode as fast as the positive electricity arrives.

The explanation of the exceedingly rapid rate of propagation of the positive column is of primary importance in any theory of the mechanism of the electric discharge. The theory which seems to me the most probable is that the passage of electricity (or, from another

point of view, the shortening of tubes of electrostatic induction) is effected by the dissociation of the molecules into atoms, in other words, that "chemical decomposition is not to be considered as an accidental attendant on the electrical discharge, but as an essential feature of the discharge, without which it could not occur" ('Phil. Mag.,' vol. 15, 1883, p. 432). Free atoms must, on this view, exist in the path of the discharge to serve as the ends of the tubes of force as they shorten. If, however, we take this view of the discharge of electricity, the chemical decomposition attendant on the discharge along the positive column cannot consist of the *consecutive* interchange of atoms between adjacent molecules, for, since on this view each atom would have to move up to the one in the adjacent molecule, the velocity of the atoms would have to be that of the discharge of the positive column, viz., about half that of light. The existence of a wind in the tube of this velocity is, *a priori*, unlikely, and the following calculation will show that it would require the expenditure of more energy than we have at our disposal.

Let us take the case of the discharge of a parallel plate condenser, the distance between the plates being 1 cm. Let F be the electromotive intensity between the plates, K the specific inductive capacity of the gas; then the energy per square centimetre of area of the condenser plate is

$$\frac{1}{8\pi}\,\mathrm{KF}^2.$$

Let N_0 be the number of atoms required to discharge unit area of the condenser; then, if σ is the density of the electricity on the condenser and ϵ the charge on each atom in electro-magnetic measure,

$$\mathrm{N}_0\epsilon = \sigma.$$

If m is the mass of one of these atoms, v the velocity with which the atoms move, their kinetic energy is

$$\tfrac{1}{2}\mathrm{N}_0 m v^2.$$

If N is the number of atoms in one gramme of the substance, then, if the charges on the atoms are the same as that deduced from electrolytic considerations,

$$\mathrm{N}\epsilon = 10^4 \text{ and } \mathrm{N}m = 1.$$

Now $$4\pi\sigma = \mathrm{KF}.$$

Making these substitutions, we find that the kinetic energy of the atoms is

$$\frac{1}{8\pi}\,\frac{\mathrm{KF}v^2}{10^4},$$

so that the ratio of the kinetic energy of the atoms to the energy in the electric field is

$$\frac{v^2}{10^4.F}.$$

Now, at atmospheric pressure, F for air is about 3×10^{12}; we have seen that $v = 1{\cdot}6 \times 10^{10}$; hence, in this case, the kinetic energy of the atoms is about 8000 times that of the electric field. If we had taken the case of a gas at a lower pressure, the disproportion would have been still greater.

For this reason, the discharge along the positive column cannot be carried by atoms travelling at the same rate as the discharge; the same argument would also be fatal to the view that the discharge takes place by the consecutive interchange of atoms between adjacent molecules. If, therefore, we are to retain the view (which seems to me to be almost established by the results of recent experiments) that the passage of electricity is effected by the dissociation of the molecules in the path of the discharge, we are precluded from supposing that in the positive column the discharge takes place by the molecules dissociating one after another, as the discharge comes up to them. In a paper in the 'Philosophical Magazine' for August, 1890, I suggested that we could reconcile the dissociation theory with the observed velocity of propagation of the discharge (of which I had, at that time, only obtained an inferior limit, and did not know that it started from the anode), by supposing that the molecules of the dielectric in the path of the discharge, before the discharge takes place, form themselves into a series of Grotthus chains, and that for the molecules which constitute any one of these chains, the dissociation and recombination go on simultaneously. This may, perhaps, be made clearer by a somewhat crude illustration.

A. B. C. D.

If A, B, C, D represent consecutive polarised molecules, the simplest view of the discharge would be to suppose A to split up into atoms, its positive atom going up to B and combining with the negative atom of that molecule; the positive atom of B is driven off, and travels to C and combines with the negative atom, and so on. On this view the velocity of the atoms would be very nearly that of the discharge which other preceding experiments have shown to be inadmissible for the positive column. If, however, we suppose that the molecules A, B, C, D, constituting a Grotthus chain, are split up simultaneously, and that while the positive atom of A combines with the negative of B, the positive atom of B is combining with the negative of C, and so on, then, in the time which elapses between

the commencement of the dissociation of a molecule to the end of the recombination of its atom with those of neighbouring molecules, a positive atom will have disappeared from one end of the chain and appeared at the other. Thus in this case, since the time taken for the decomposition and recombination of the molecules is independent of the length of the chain, whatever the length of the chain may be, the positive charge will travel from one end of the chain to the other in the same time, and thus the velocity of the discharge will be proportional to the length of the chain. In the paper referred to above, it is suggested that the high velocity of the discharge of the positive column is attained by the formation of Grotthus chains of suitable length, the column thus consisting of a series of separate discharges, the length of each discharge being that of the Grotthus chain; these separate discharges are made manifest in the stratification which is so striking a feature of the positive column, the space between the bright portions of two striæ corresponding to the length of the Grotthus chain; thus, on this view, the stratifications are the manifestations of the machinery which enable the positive discharge to travel at such a rate. In the paper in the 'Philosophical Magazine' it is shown that this view of the discharge agrees well with what is known as to the behaviour of striæ.

The preceding experiments show that the tubes of force which we imagine as stretching round the circuit, and contracting when the discharge takes place, are anchored almost completely to the negative electrode. When the discharge begins to pass, the ends of these tubes near the positive electrode will be agitated in an approximately periodic way, electrical vibrations will travel along the tubes with the velocity of light, and, as one end of the tube is fixed, these will form stationary vibrations; these stationary vibrations may be conceived to give the molecules of the gas in the tube a certain periodicity of arrangement, and lead to the formation of the Grotthus chains of definite lengths, required by the preceding explanation. It will be seen that this would make the position of the striæ depend on that of the negative electrode, so that when the latter is moved the striæ ought to be displaced; this effect has been observed by Goldstein.

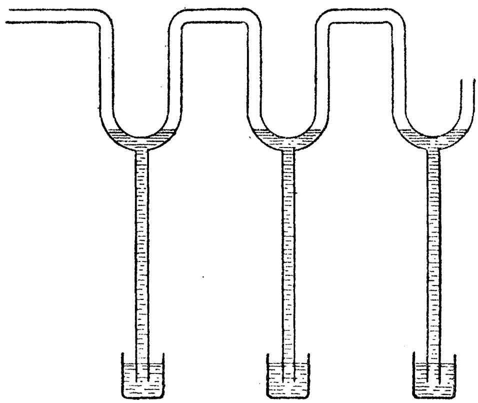
As an alternative to the preceding view, it might perhaps be urged that the luminosity of the positive column outruns the positive discharge. This view, however, seems to be quite untenable in the face of Spottiswoode's and Moulton's experiments on the sensitive state of the electric discharge ('Phil. Trans.'), for the relief effects observed in their experiments seem to show, without ambiguity, that the positive luminosity is coincident with free positive electricity.

We have also no evidence that a gas can be made luminous by

sudden alterations in the electric or magnetic intensity of the field in which it is placed, unless these are accompanied by the passage of free electricity through the gas.

In order to get some further information about the laws which govern the propagation of the positive column, some experiments were made in which the discharge had to pass from the gas to mercury and out again from the mercury to the glass several times in its passage from B to G (fig. 1). The arrangement by which this was done is shown in fig. 3. Pieces of glass tubing, bent as in the figure, with baro-

FIG. 3.



metric tubes filled with mercury attached to their lowest points, were inserted in the circuit between B and G. By raising or lowering the vessels into which the ends of the barometer tubes dipped, mercury could be poured into or taken out of the bends in the tube. There were in all six of these mercury electrodes introduced between B and G. The displacement of the images, as seen through the telescopes, was observed (1) when the mercury was below the level of the tops of the barometer tubes, and (2) when the mercury filled the bends of the tube, blocking it up completely in six places. No appreciable difference could be observed between the displacements of the images in the two cases. When, however, the mercury was in the tube, the discharge had very much greater difficulty in getting through than when its path was not interrupted by the columns of mercury; this was shown by the luminosity in the main circuit being very much fainter, and that in a branch circuit leading to the air-pump much brighter, when the mercury was in the tubes than when it was not.

It seems, I think, pretty clear that what takes place when the

mercury is in the tube is something of the following kind. The positive electricity rushes from the anode down the tube until it reaches the first mercury plug; it attracts the negative electricity to the nearer end of this plug, and repels the positive to the other end; this positive electricity begins to leave the mercury immediately and travels down to the next mercury plug.

The positive electricity which travels up to the first mercury plug and the negative electrification it produces on the mercury form an electrical double layer which takes some time to disappear, longer probably than the time taken by the electricity to travel from one end of the tube to the other. The time the luminosity takes to travel from B to G will thus not be much affected by the mercury plugs; but, as the discharge leaves behind it a series of electrical double layers on the sides of the mercury columns nearest the positive electrode, the difficulty of forcing electricity through the tube will be temporarily increased.

It is, I think, worthy of remark that the effects produced by displacement currents render it impossible to predict the velocity of the discharge of electricity through a rarefied gas. For, if we consider the processes which accompany this discharge, we have, first, the production of the electric field; this causes an increase in the electric displacement, and in consequence produces magnetic effects; and the displacement current behaves as if it had inertia, travelling through the medium with the velocity of light. When the intensity of the field is increased sufficiently to cause discharge, the electricity passes through the gas, and the electric field disappears. The convective current formed by the passage of the free electricity is balanced by the displacement current in the opposite direction, due to the disappearance of the electric displacement. The discharge, therefore, does not produce a magnetic field, and has, therefore, no inertia. The velocity of propagation of this discharge will, therefore, be governed by different laws from those which control currents producing a magnetic field, and need not, therefore, have anything to do with the velocity of propagation of light through the medium.

By adjusting the circumstances under which the preliminary charging takes place, we can separate the magnetic force due to the charging by as long an interval as we please from the discharge. We can also, by charging sufficiently slowly, make the magnetic force at any instant as small as we please; thus it is conceivable that we might have a copious discharge of electricity through a gas practically unaccompanied by magnetic force.

The very remarkable action of a magnet on the electric discharge is not inconsistent with this view, as on it the discharge consists of two equal and opposite currents, of which only one is

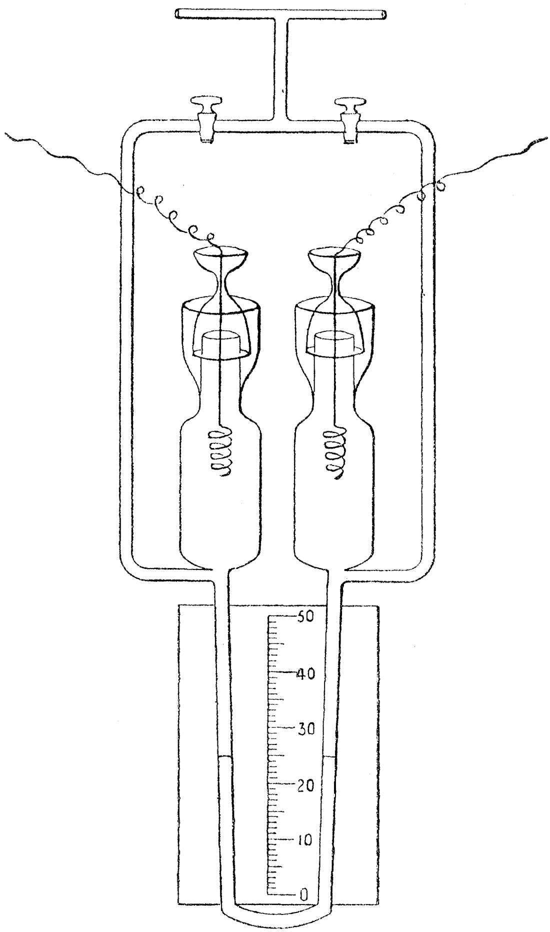
visible: we see the action on the visible current, but not the opposite one on the other.

The most obvious explanation of the remarkable difference in the behaviour of the discharges from the anode and cathode is that it arises from some difference in the chemical action between the gas and the two electrodes. I have made a series of experiments in order to test this view, and have been led to the conclusion that an explanation of this effect by purely chemical action is delusive. At the same time I think that the necessity for the existence of some action between the gas and the electrode is shown by the following experiment. In the 'Philosophical Magazine,' vol. 29, 1890, p. 441 (On the Passage of Electricity through Hot Gases), I described an experiment in which cold electrodes were plunged into a hot gas, such as iodine, heated until it dissociated, when it was found that no current passed through the gas until the electrode got hot, when it passed freely. The effect produced by the cold electrodes seemed too abrupt to be altogether due to the cooling of the adjacent gas by the electrodes. I therefore made the following experiment in order to test this point. If the effect is due to the cooling of the gas, the temperature of the electrodes when the system begins to conduct ought not to vary much, whatever may be the material of which they are made; while if the effect were due to chemical action between the gas and the electrodes, we should expect considerable variation with different electrodes in the temperature at which conduction begins. I therefore attempted to measure roughly the temperature at which conduction began (*a*) when the electrodes were iron, (*b*) when they were platinum. This was done by making one of the electrodes into a thermopile placed in circuit with a dead-beat galvanometer; in case (*a*) the thermopile consisted of an iron plate with a German-silver wire, in case (*b*) of platinum foil and a German-silver wire. The electrode used as the thermopile was dropped cold into the hot gases and connected up with the main circuit. When the galvanometer in the main circuit first began to show decided indications of the passage of a current, the observer who was watching this galvanometer called to the observer at the dead-beat galvanometer in the thermopile circuit, and this observer read the deflection of this galvanometer. From this reading the temperature of the hot junction could approximately be determined. The experiment was repeated, using, instead of the iron-German silver couple, a platinum-German one, the platinum foil being wound round an iron plate to make it heat up at approximately the same rate as the first couple. It was found that the conduction began at a much lower temperature when the electrode was iron than when it was platinum, indicating that some action between the electricity and the gas was necessary for conduction. I could not,

however, detect any difference between the positive and negative electrodes in this respect. The gases in which this effect was found were I, HCl, and HI.

I next endeavoured to see if I could detect any difference in the chemical action of chlorine on a metal positively or negatively electrified. This was done in the following way :—A and B (fig. 4) are

FIG. 4.



two coils of copper wire, of the same length, made from the same hank of wire, and as nearly as possible alike in all respects: these are filled into two equal vessels which are connected by a U-tube

filled with sulphuric acid, which serves to indicate any difference in the absorption of the chlorine by the two coils of wire. The vessel was exhausted and then filled with chlorine, and A and B were placed in parallel with the electrodes of an induction coil, giving sparks about an inch and a half long. In this way one coil was positively and the other negatively electrified, and any difference in the rate of combination of the chlorine with the metal would show itself by the motion of the sulphuric acid in the gauge. Only a very small motion of the sulphuric acid occurred, and this seemed to be accidental, as it was not reversed on reversing the coil. The difference between the rate of combination of chlorine with a positively and negatively electrified metal must therefore be small.

Again, if the difference between the behaviour of the positive and negative discharge were due to purely chemical action between the gas and the electrode, we should expect this difference to be absent in the case where the electrodes consisted of a volatile liquid or solid, and the gas was the vapour of the electrode. I tried three cases of this kind: one in which the electrodes were water and the gas water vapour; a glass tube was completely filled with water, then placed on the pump, and the water boiled away until only just enough was left to serve as electrodes; the tube was then sealed off and cooled down until the vapour pressure was low enough to allow the electric discharge to pass without difficulty; this tube, however, had all the usual characteristics of the discharge through vacuum tubes, including the negative dark spaces and the striations. In the next experiment a similar tube was taken, the water being replaced by bromine; this, too, showed the usual differences between the discharge at the two electrodes, and similar appearances were presented by a tube in which the electrodes were re-distilled arsenic and the gas arsenic vapour.

Another difficulty in the way of explaining the difference at the two electrodes by chemical action is that no difference seems to be made in the appearance when a strongly electronegative gas, such as chlorine, is substituted for a strongly electropositive one, such as hydrogen.

I next endeavoured to get rid of the electrodes altogether by trying to get a circular discharge in an exhausted re-entrant tube without any electrodes. For this purpose the primary was generally a piece of copper rod bent into a horse-shoe shape; the secondary circuit was an endless circular glass tube from which the air had been exhausted. A Leyden jar, charged by a Wimshurst machine, was discharged through the primary, and produced by induction an electromotive force round the exhausted tube. When the secondary was not shielded from the electrostatic induction of the primary, it was

filled with a uniform glow whenever the discharge passed through the primary circuit, but, when the electrostatic induction was shielded off by pieces of wet thin blotting paper connected to earth, no glow could be observed, though the wet blotting paper is not a sufficiently good conductor to shield off electromagnetic induction.

The maximum integral electromotive force round the secondary is shown to be VM/L, where V is the difference between the potentials of the coatings of the jar before discharge, L the coefficient of self-induction of the primary circuit, and M the coefficient of mutual induction between the circuits. Though in my experiments this was greater than the electromotive force requisite for a discharge through gas at the same density between terminals separated by the length of the tube, not the faintest glow could be detected. All my efforts to get a discharge through the secondary have so far been unsuccessful,* and I feel sure that the ease of getting a discharge without electrodes, say by the motion of the upper regions of the earth's atmosphere across the lines of magnetic force, has been much over-estimated. Until, however, we have got a discharge without electrodes through nothing but the gas itself, we are unable to say whether the passage of the discharge from the positive to the negative electrode which occurs in gases is a consequence of having matter in two states in the path of the discharge, or whether it is an example of a more general law, that, whenever tubes of electrostatic induction shorten in a conducting circuit, they do so in the direction of the electric displacement.

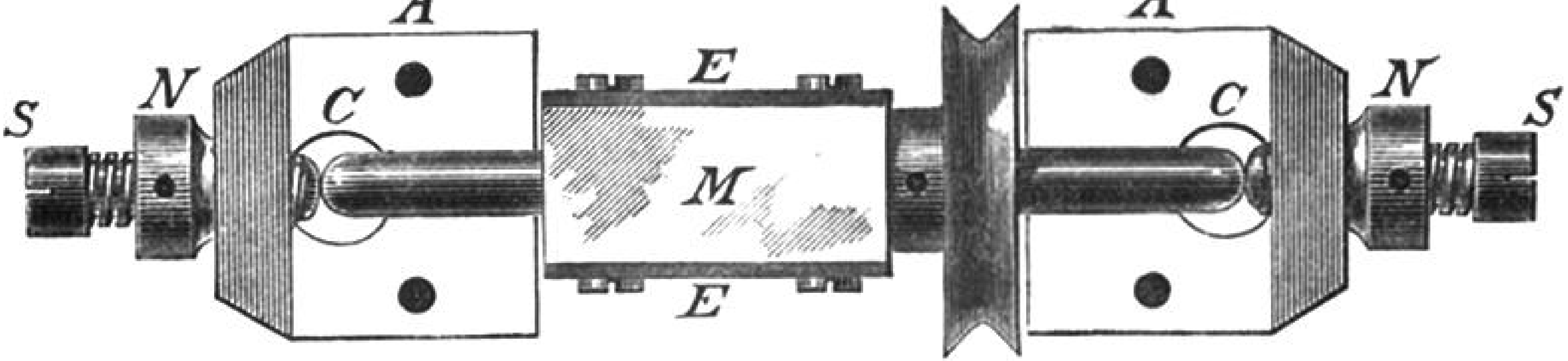
In conclusion, I have much pleasure in thanking Mr. Bartlett and Mr. Everett for the assistance they have given me in the course of this investigation.

II. "Note on the Present State of the Theory of Thin Elastic Shells." By A. E. H. Love, M.A., St. John's College, Cambridge. Communicated by Lord Rayleigh, Sec. R.S. Received January 3, 1891.

In a paper read before the Royal Society in February, 1888, and published in 'Phil. Trans.,' A, of that year, I advanced a theory of the mode of deformation that takes place when a thin shell is vibrating. The theory was founded on the form of the potential energy function, obtained by a method adapted from that of Kirchhoff for plates. It appears that, in case there are no surface-stresses on the faces of the shell, this function consists of two terms, of which one contains a certain function W_2 and the thickness $2h$ as factors, and

* Since this paper was sent in to the Royal Society, I have succeeded in getting a discharge without electrodes through a tube about 45 cm. in circumference. The discharge did not exhibit any signs of stratification.—Jan. 23, 1891.

FIG. 2.



Plan of Revolving Mirror. Upper halves of Bearings, A, carrying Oil Cup removed.